Sustainable Economy Research Group (S.E.R.G.)
Working Papers in Economics

"Equity-based additional downstream allocation methods for Scope 3 emissions"

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Reference Details

ID: 2026 - 1

Key-words : *Allocation, Upstream emissions, Axiomatic, Equity and supply chain reconstruction*

Published : 2026 - June

Website : https://www.serg.paris/working-papers

Equity-based additional downstream allocation methods for Scope 3 emissions

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June 1, 2026

Abstract

Amid growing pressure to reduce greenhouse gas emissions, corporations increasingly commit to cutting emissions across their supply chains, including those generated by their upstream suppliers. Because these emissions lie beyond firms' operational control, companies resort to using coercive supplier management strategies that can shift mitigation burdens to less powerful upstream firms. In response, we present alternative principles for allocating upstream emission reduction responsibility using an axiomatic framework. In particular, we characterize methods that distributes mitigation burdens downstream according to an exogenous fairness metric. We apply our alternative allocation methods to reconstructed multi-tier supply chains derived from the Structural Path input–output database analysis method paired with the Competitiveness Research Network firm-level characteristics database. We find that while downstream logic dominates global cost-sharing outcomes, allocation principles influence their magnitude and distribution across industries and countries. This work offers a foundation for advancing equity considerations in supply-chain-level emission mitigation.

Keywords

- Allocation
- Upstream emissions
- Axiomatic

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- Equity
- Supply chain reconstruction

Highlights

- Equity-based downstream methods for supply chain emission responsibility allocation
- Formal definition and axiomatic characterization
- Multi-tier supply chain reconstruction from input-output data
- Dominance of downstream allocation logic in global outcomes
- Industry and region outcome heterogeneity across equity metrics

CRediT Authorship

- Marine Kohler : Conceptualization, Data curation, Methodology, Software, Visualization, Writing – original draft, Writing – review and editing
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1 Introduction

Anthropogenic climate change is severely disrupting human societies. To limit its impact, greenhouse gas (GHG) emissions need to be curbed so as to reach global *Net Zero* between 2050 and 2075 [1]. [1] The 2015 Paris Agreement formalizes this objective by establishing country-level commitments among its 195 signatories [2].

In this context, firms are increasingly taking voluntary action to gain a competitive advantage [3] and preserve their social license to operate, i.e. their stakeholders' acceptance and approval of their activities [4]. In particular, firms commonly set and publicize voluntary emissions reduction targets to signal climate leadership. To demonstrate their adequacy relative to the global Net Zero goal, these targets typically rely on third-party certification, most notably by the *Science Based Targets initiative* (SBTi).[2]

Drawing from the absolute environmental sustainability assessment literature (reviewed in Section 2), SBTi provides guidance tailored to firm characteristics to define science-based emissions reduction targets (SBT). Although firms are offered several options of target perimeters, SBTi recommends or requires that targets cover Scope 3 emissions whenever they represent a significant share of a company's footprint [7]. Scope 3, or indirect, emissions arise in suppliers' or customers' facilities and are necessary for firm activity, including emissions from upstream raw material extraction or downstream energy use of sold products [8]. This shared responsibility mechanism is designed to minimize global supply chain emissions abatement costs [9]. It has also contributed to SBTi's exponential growth, particularly among smaller business-to-business firms [10, 11], as addressing Scope 3 emissions compels firms to either revise procurement toward suppliers with existing SBTs or engage suppliers to adopt SBTs.

However, shared Scope 3 abatement responsibility may shift disproportionate emissions abatement burdens onto supplier-dependent firms. Research highlights that firms often enforce social and environmental standards through coercive mechanisms such as contract conditions, financial penalties, or termination threats [12, 13, 14], which also appears to be encouraged by SBTi and corporate climate NGOs [15, 10, 16]. Further, the benefits of supply-chain-wide sustainability initiatives could accrue mainly to buying firms [14]. In this context, small and medium enterprises that are quasi-

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[1] Net Zero refer to a state of equilibrium between the yearly amount of emitted and captured and stored GHG

[2] Launched in 2015 by a coalition of non-governmental organizations, SBTi reports that 11,000 companies either plan to set or have set emissions reduction targets under its framework, representing 41% of global market capitalization and 25% of global revenue [5], and continues to expand across industries, geographies, and firm sizes [6].

exclusive suppliers to large corporations may be compelled to reduce emissions despite low business returns, while diversified upstream firms could resist client demands [17]. These coercive practices contradict existing SBTi's efforts to propose allocation methods that distribute emissions abatement responsibility across firms according to equity principles [18, 7], and call into question whether a supplier be coerced into reducing their emissions beyond their defined fair share by a powerful client.

To mitigate coercive supplier engagement practices, this paper challenges the current Scope 3 overlapping responsibility by introducing novel additive equity-embedded upstream Scope 3 emissions allocation methods. We draw from microeconomic theory to operationalize fair allocation principles in a multi-tier supply chain setting and follow an axiomatic approach to establish their theoretical merits and uniqueness. In the absence of firm-level empirical data, we propose a new method to derive average supply chains from input–output databases. This allows us to demonstrate the applicability of these allocation methods and discuss their empirical strengths, limitations, and complementarity. Ultimately, the introduced allocation methods could inform voluntary corporate supply chain decarbonization subsidies or be used to reform targets setting standards.

The paper is organized as follows. Section 2 reviews the literature on absolute sustainability assessment, allocation methods, and related theoretic work. Section 3 presents the axiomatic analysis of cooperative supply chain allocation methods, followed by an empirical application in Section 4, and a brief conclusion in Section 5.

2 Literature review

Despite the relative recency of SBT, extensive empirical and theoretical literature exists on corporate supplier engagement practices and on the allocation of the environmental burdens to responsible parties.

2.1 Absolute sustainability assessment and SBTi

The absolute sustainability assessment (AESA) literature emerged following the development and popularization of the planetary boundaries framework, which defines biophysical and biochemical limits humanity must not exceed to avoid unforeseeable and irreversible environmental disruption [19, 20]. For example, the latest framework estimates that atmospheric CO_2 concentrations should remain below 350 ppm to prevent cascading climate change impacts. In this context, the "safe operating space" refers to the buffer between Holocene background levels and risk thresholds; remaining within this space preserves environmental conditions that have historically supported human development [19].

Assessing the absolute sustainability of a region, company, agent, or object involves comparing its environmental impacts to its fair share of the safe operating space to determine whether it contributes to breaching planetary boundaries. This requires choosing an accounting approach and system boundaries to attribute environmental impacts to the system studied, and selecting an allocation method—a method that assigns shares of the safe operating space to individual agents [21]. Because allocation methods are based on differing principles of equality and equity, choosing one is inherently an ethical decision [22].

SBTi can be seen as the most successful effort to mainstream elements of AESA, including attribution and allocation methods, and embed them in corporate strategy. Despite the standard's success and methodological diversity, critics argue that SBTi—while presenting itself as scientific and apolitical—largely overlooks existing work on equitable allocation. SBTi methods typically rely on grandfathering for target setting, a principle widely criticized for reinforcing country-level inequalities [23]. Moreover, some SBTi methods draw on International Energy Agency (IEA) mitigation scenarios to define fair share of safe operating spaces, even though these scenarios give limited attention to distributive justice [23].

2.2 Allocation methods

Although the rise of absolute sustainability assessment and SBTi renewed attention to allocation methods, distributing the burden of mitigating a shared externality among interdependent actors is not a new challenge.

Note that in the following, in line with the general economics literature, an allocation method refers to any method that distributes emissions abatement responsibilities among actors. This definition is related to, but wider than the one proposed for allocation methods in AESA, as it also covers attribution methods. For instance, in AESA, consumption-based accounting is considered an attribution method, as it assigns the emissions generated by production to the final demand. However, as discussed below, it is presented as a possible allocation method in general economics, as it generally contributes to allocating emissions abatement responsibilities to agents (see for instance [24]). [3]

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[3] From an AESA perspective, one could argue the proposed allocation methods in this paper rather constitute attribution methods as they distribute emissions among co-responsible agents. As such, they can be combined with other allocation methods. A detailed paragraph describing how they could be used in AESA or target setting is available in the concluding

Modern economics—especially welfare economics—has largely relied on a utilitarian perspective, where the fairest (or least controversial) allocation minimizes total abatement costs [25]. However, at the country level, the unprecedented and uneven costs of GHG mitigation and climate adaptation have led to increasing criticism of utilitarian burden-sharing.

In response, alternative equity principles have been proposed to support global agreement [26]. An early example of an alternative allocation method can be derived from Leontief's work in introducing Input-Output tables, which maps economic flows between region–industry pairs and allow estimating how meeting one monetary unit of demand in a given country and industry drives production upstream. Coupled with estimates of marginal monetary environmental impacts estimates [27], input-output tables enabled later environmental researchers to allocate the impact of the upstream production to the downstream demand, also dubbed "consumption-based accounting". This is often viewed as fairer to developing countries that produce exports not directly consumed or used by their populations [28]. Since then, numerous allocation principles have been developed; recent reviews include Zhou et al. [24] and Bai et al. [29]. Bai et al. classify these into 11 broad approaches, ranging from backward-looking methods (e.g., economic contribution, where shares reflect current economic performance) to forward-looking ones (e.g., development rights approaches, which ensure countries can overcome poverty).

Despite this diversity, allocation principles are not equally used. At the firm level, the limited AESA literature applies economic contribution, basic needs and preferences (allocating shares by merit order to ensure basic human needs are met), and equality principles [29]. Outside AESA, utilitarianism remains dominant [24], and no consensus has yet emerged on how to allocate the climate safe operating space among countries [30, 31, 32].

2.3 Supply chain allocation

Beyond top-down allocation, microeconomic theory provides allocation method to share abatement responsibilities in a supply chain setting. Notable contributions include Sunar and Plambeck [33], who examine how emissions should be divided among co-products, and a series of papers by Gopalakrishnan et al. [9, 34] that explores upstream emission responsibility of shared industrial processes. Similarly, van den Ende et al. [31] consider a broader class of network structures that include cycles and rely on concepts from network and decision theory to propose novel consumption emissions allocation methods at the country and industry levels.

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remarks section.

However, Ciardiello et al. [35] establish that the game theory literature largely overlooked firm-level supply chain emissions allocation. In an attempt to bridge this literature gap, they draw from the polluted river problem literature [36] to introduce a mathematical representation of an upstream supply chain and introduce three allocation rules that fit their mathematical representation [35].

The river problem was first introduced by Ni and Wang [37] and considers how to allocate cleaning costs to polluting agent located along the segments of a river, which is modeled as a directed tree graph. The analogy with our framework is straightforward: the river corresponds to a supply chain network, and cleaning costs represent direct emissions to abate. In their seminal paper, Ni and Wang [37] propose two allocation rules, *Standalone* and *Upstream Equal Sharing*, which respectively considers each agent responsible for their local pollution, and distribute cleaning cost across upstream agents. A counterpart method, called Downstream Equal Sharing, is proposed by [38]. Li et al. [39] extend the domain of solutions by proposing a *Weighted Upstream Sharing* allocation rule, in which responsibilities are weighted by an exogenous metric [39] (a similar concept was previously discussed by [40]).

Borrowing on the river problem and these solutions, we operationalize equity allocation principles in multi-tiers supply chains in the following section to share emissions abatement responsibility among co-dependent actors.

3 Allocation problem and solutions

This section defines our supply chain allocation problem, reviews the allocation methods considered and their connections to the literature presented above, and presents axiomatic characterizations of these methods.

3.1 The model

Let $N = \{1, \ldots, n\}$ be a finite set of firms. The firms engage in supplier-customer relationships, which we represent as a matrix $s \in \{0,1\}^{n \times n}$. Formally, $s_{ij} = 1$ implies that firm i supplies some goods to firm j, and $s_{ij} = 0$ implies that i supplies nothing to firm j. We use the convention $s_{ii} = 0$ for each $i \in N$. These relationships can also be interpreted as a directed graph.

A supply chain is a sequence of firms $i_1, i_2, \ldots, i_k$ such that $s_{i_1 i_2} = 1, \ldots, s_{i_{k-1} i_k} = 1$. If there exists a supply chain from i to j we use the notation iSj. We denote by $\uparrow_S (i) = \{j \in N : iSj\}$ the set of all firms that i supplies directly, or indirectly. Likewise, we denote by $\downarrow_S (i) = \{j \in N : jSi\}$ the set of all firms that are supplying directly, or indirectly, firm i.

Let 1 be one of the firms in our finite set of firms. From now on, we restrict our set N to the firms that supply 1, directly or indirectly. By convention, we set $\uparrow_S(i) = \emptyset$. In this paper, we assume that each firm directly supplies at most one other firm in the graph, i.e., there exists at most one $j \in N$ such that $s_{ij} = 1$ for each $i \in N$. Note that this does not mean our problem applies only to firms with a single client, but only that firms cannot supply two distinct actors in 1's supply chain, i.e. they make one unique contribution to the initial 1's product. However, a firm may have several suppliers. Our graph thus forms a tree directed toward a sink 1.

For all firms i in N, let c_i be the direct greenhouse gas emissions they generate in order to supply firm 1 with enough input for it to produce one unit of its own production.

Definition 1. A supply chain emission allocation problem is a tuple (N, c, s). For simplicity, we use c instead of the whole tuple. The domain of all problems is denoted by $\mathcal{C}$.

Example 1. Let $N = \{1, \ldots, 6\}$. The supplier-customer relationships between the firms can be represented as directed graph (see Figure 1). All firms supply directly or indirectly firm 1, i.e., $\downarrow_S(1) = \{2, 3, 4, 5, 6\}$. By convention, $\uparrow_S(i) = \emptyset$. In addition, $\uparrow_S$: $\downarrow_S(2) = \{3, 4\}$, $\downarrow_S(3) = \downarrow_S(4) = \downarrow_S(5) = \downarrow_S(6) = \emptyset$, $\uparrow_S(2) = \uparrow_S(4) = \uparrow_S(5) = \{1\}$, and $\uparrow_S(3) = \uparrow_S(6) = \{1, 2\}$. The vector of direct emissions is $c = (2, 1.5, 1, 0.5, 6, 1)$.

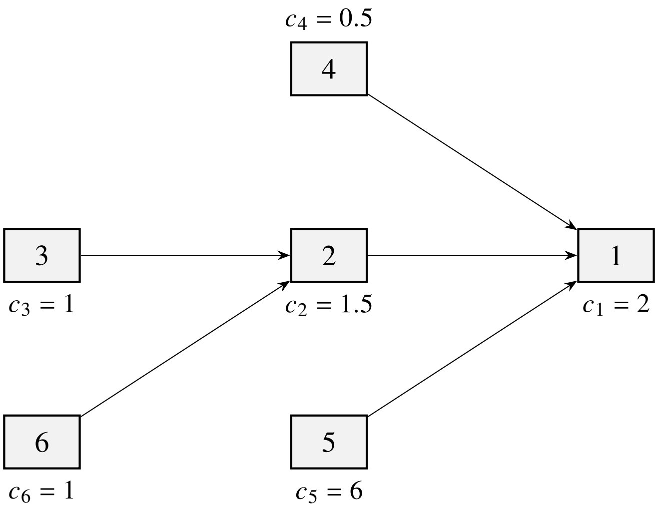

Figure 1: An example supply chain problem

3.2 Emission allocation methods

An allocation method is a map $\varphi : C \longrightarrow \mathbb{R}^n_+$ that assigns an emission allocation vector to any supply chain emission problem, and verifies $\sum_{i\in N} \varphi_i(c) = \sum_{i\in N} c_i$. Essentially, it performs an allocation of the direct emissions among the firms, and it can be used to distribute emissions mitigation efforts among co-dependent firms. This section presents several allocation methods. The first allocation method is straightforward as it requires that each firm takes responsibility for its own direct emissions.

Definition 2. The **Standalone** method is defined, for each $c \in C$, as

$$\forall i \in N, \quad \varphi_i^S(N, c, s) = c_i.$$

Yet, in line with consumption-based accounting, it can be argued that the downstream firm bears partial responsibility for any emissions occurring upstream their supply chain. Thus, the second allocation method assigns to each agent a share of the direct emissions generated by its suppliers. Formally, the allocation method distributes the direct emissions c_j of each firm j equally among all the firms that are directly or indirectly supplied by j.

Definition 3. The **Downstream Equal Sharing** method is defined, for each $c \in C$, as

$$\forall i \in N, \quad \varphi_i^{DES}(N, c, s) = \sum_{j\in \downarrow_S(i)\cup\{i\}} \frac{c_j}{|\uparrow_S(j)\cup\{j\}|}.$$

Note that we consider only downstream emissions sharing (i.e. distributing emissions of suppliers to clients) as current corporate engagement efforts typically focus on pushing upstream suppliers to manage their emissions. A symmetric upstream equal-sharing approach could also be considered, but it lies beyond the scope of this study.

The third allocation method extends the Downstream Equal Sharing method to allocates emissions proportionally to an exogenous weighting metric. This weighted approach has first been proposed by [39] for polluted river problems. However, their approach is based on an upstream sharing rather than a downstream sharing. This weighted approach enables a more nuanced allocation that takes into account characteristics of the firm such as its level of environmental performance, its size or its capacity to pay, in line with equity approaches outlined by [29].

Definition 4. Take any $m \in \mathbb{R}^n_{++}$. The associated **Downstream Metric Sharing** method is defined, for each $c \in C$, as

$$\forall i \in N, \quad \varphi_i^{D(m)S}(N, c, s) = \sum_{j\in \downarrow_S(i)\cup\{i\}} \frac{m_i}{\sum_{k\in\uparrow_S(j)\cup\{j\}} m_k} c_j.$$

Example 2. Consider the supply chain emission problem defined in Example 1. We now illustrate how the Standalone, Downstream Equal Sharing and Downstream Metric Sharing would apply on the proposed supply chain structure.

Applying the Standalone method is straightforward as each firm gets assigned their direct emissions.

We follow algorithm 1 in Appendix to apply the Downstream Equal Sharing method. Since firm 1 has no downstream clients, the totality of the firm's emissions stay assigned to it. Firm 2 on the contrary is a supplier of firm 1. Its emissions thus get equally shared between firm 1 and itself. Similarly, firm 3 is a supplier of firms 2 and 1 and its direct emissions are equally distributed between firm 1, firm 2 and itself, and so on. After considering each firm, allocations for each node are :

$$\begin{aligned}
\varphi_1^{DES} &= 2 \times \frac{1}{1} + 1.5 \times \frac{1}{2} + 1 \times \frac{1}{3} + 0.5 \times \frac{1}{2} + 6 \times \frac{1}{2} + 1 \times \frac{1}{3} \approx 6.66 \\
\varphi_2^{DES} &= 1.5 \times \frac{1}{2} + 1 \times \frac{1}{3} + 1 \times \frac{1}{3} \approx 1.41 \\
\varphi_3^{DES} &= 1 \times \frac{1}{3} \approx 0.33 \\
\varphi_4^{DES} &= 0.5 \times \frac{1}{2} = 0.25 \\
\varphi_5^{DES} &= 6 \times \frac{1}{2} = 3 \\
\varphi_6^{DES} &= 1 \times \frac{1}{3} \approx 0.33.
\end{aligned}$$

Similarly, we follow algorithm 2 in Appendix to apply the Downstream Metric Sharing method. For the sake of simplicity and to avoid introducing further data, we use direct emissions levels as our weighting metric. Since firm 1 has no downstream clients, the totality of the firm's emissions stay assigned to it. Firm 2 on the contrary is a supplier of firm 1. Its emissions thus get shared between firm 1 and itself, proportionally to the magnitude of their direct emissions. Similarly, firm 3 is a supplier of firms 2 and 1 and its direct emissions are distributed proportionally to the magnitude of their direct emissions between firm 1, firm 2 and itself, and so on. After considering each firm, allocations for each node are :

$$\begin{aligned}
\varphi_1^{D(m)S} &= 2 \times \frac{2}{2} + 1.5 \times \frac{2}{2+1.5} + 1 \times \frac{2}{2+1.5+1} + 0.5 \times \frac{2}{2+0.5} + 6 \times \frac{2}{2+6} + 1 \times \frac{2}{2+1} \approx 5.86 \\
\varphi_2^{D(m)S} &= 1.5 \times \frac{1.5}{2+1.5} + 1 \times \frac{1.5}{2+1.5+1} + 1 \times \frac{1.5}{2+1.5+1} \approx 1.31 \\
\varphi_3^{D(m)S} &= 1 \times \frac{1}{2+1.5+1} \approx 0.22 \\
\varphi_4^{D(m)S} &= 0.5 \times \frac{0.5}{2+0.5} = 0.1 \\
\varphi_5^{D(m)S} &= 6 \times \frac{6}{2+8} = 4.5 \\
\varphi_6^{D(m)S} &= 1 \times \frac{1}{2+1.5+1} \approx 0.22.
\end{aligned}$$

3.3 Axioms and characterizations

This subsection presents axiomatic characterizations of our allocation methods. An axiomatic characterization decomposes a method into elementary properties, called axioms, that collectively and uniquely determine the corresponding allocation method. These axioms often capture allocation principles that are particularly relevant to the setting at hand. In this paper, we adapt axioms from the polluted river literature to our framework and use them to provide normative justifications for our allocation methods. Specifically, we show that each allocation method is uniquely characterized by a set of desirable axioms that it alone satisfies.

For each problem $c \in C$ and each firm $k \in N$, denote by c^k the direct emission vector defined as $c_i^k = 0$ if $i = k$ and $c_i^k = c_i$ otherwise. The vector c^k represents a scenario in which firm k reduces their direct emissions to zero. The following axioms then examine the effect of this change on the allocations of the firms supplied by k. This effect can also be interpreted as the contribution of those firms to the emissions of k, in the sense of identifying the portion of k's emissions that was attributable to them.

The first axiom is based on the principle that a firm should only be held responsible for their emissions, and the emissions generated by the firms that supply it. Consequently, firms that are not supplied by firm k—the firm reducing its direct emissions—should not bear any responsibility. This axiom formalizes the idea by requiring that the allocation for any firm not supplied by k remains unchanged when k reduces its emissions.

Independence to Irrelevant Suppliers (IIS). For each $c \in C$ and each $k \in N$,

$$\forall i \notin \uparrow_S (k), \quad f_i(c) = f_i(c^k).$$

The next axiom, Symmetric Contribution, builds on the principle of Independence from Irrelevant Suppliers. It states that any two firms supplied by k should be affected equally by changes in emissions from k. This axiom embodies a fairness criterion, asserting that all firms dependent on a given supplier should share equal responsibility for that supplier's emissions.

Symmetric Contribution (SC). For each $c \in C$ and each $k \in N$,

$$\forall i, j \in \uparrow_S (k) \cup \{k\}, \quad f_i(c) - f_i(c^k) = f_j(c) - f_j(c^k).$$

The next axiom, m-Balanced Contribution, refines the idea behind Symmetric Contribution by stating that the impact on the firms supplied by k should be proportional to an exogenous metric $m \in \mathbb{R}^n_{++}$, thereby incorporating social considerations into the fairness criterion. Indeed, firms differ in terms of environmental performance, size, and capacity to pay; thus, an equal division of responsibility may be unfair when these factors are taken into account.

m-Balanced Contribution (m-BC). There exists an $m \in \mathbb{R}^n_{++}$ such that, for each $c \in C$ and each $k \in N$,

$$\forall i, j \in \uparrow_S (k) \cup \{k\}, \quad m_j \times (f_i(c) - f_i(c^k)) = m_i \times (f_j(c) - f_j(c^k)).$$

The final axiom is conceptually opposite to the previous three. Rather than being responsible for their suppliers' emissions, firms have the option to refuse any form of compensation or assistance from and to others. This axiom captures that idea by requiring that the firms supplied by k remain unaffected by changes in k's direct emissions.

Null Contribution (NC). For each $c \in C$ and each $k \in N$,

$$\forall i \in \uparrow_S (k), \quad f_i(c) - f_i(c^k) = 0.$$

We now have the necessary groundwork to present the axiomatic characterizations of our emission allocation methods. The Independence from Irrelevant Suppliers axiom is a common requirement satisfied by all allocation methods. Combining this axiom with any of the *contribution* axioms yields a complete characterization of an allocation method.

Theorem 1. An allocation method is the

1. **Downstream Equal Sharing** method φ^{DES} if and only if it satisfies Independence to Irrelevant Suppliers (IIS) and Symmetric Contribution (SC).
2. **Standalone** method φ^{S} if and only if it satisfies Independence to Irrelevant Suppliers (IIS) and Null Contribution (NC).
3. **Downstream Metric Sharing** method $\varphi^{D(m)S}$, for some $m \in \mathbb{R}^n_{++}$, if and only if it satisfies Independence to Irrelevant Suppliers (IIS) and m-Balanced Contribution (m-BC).

Figure 2 provides an overview of Theorem 1.

Proof. We provide an unified proof. It is clear that each method satisfies its corresponding axioms, thus this part of the proof will be omitted. To show uniqueness, we proceed by induction.

Consider any φ satisfying one of the combinations of axioms stated in the Theorem. Consider any $c \in C$. Let us show that $\varphi(c)$ is uniquely determined in any case. To that end, we proceed by induction on the firms with zero emission. The set of zero coordinates of c is denoted by $0(c)$.

Initialization: If $|0(c)| = n$, then $c = \varphi(c) = (0, 0, \ldots, 0)$ by definition of allocation methods.

Hypothesis: Assume that there exists a $W \leq n$ such that $|0(c)| = W$ and such that $\varphi(c)$ is uniquely determined. Let us show that if $|0(c)| = W - 1$, then $\varphi(c)$ is uniquely determined.

Consider any non-zero coordinate of the vector c and let us refer to it as k. By the induction hypothesis, it is clear that $\varphi(c^k)$ is uniquely determined.

By combining (SC) or (m-BC) with the induction hypothesis and the fact that $\sum_{i \in N} \varphi_i(c) = \sum_{i \in N} c_i$, one can generate $n - k + 1$ linearly independent equations containing $n - k + 1$ unknowns. These equations form a solvable system with a unique solution. Therefore, $\varphi_i(c)$ is uniquely determined for each $i \in \uparrow_S (k) \cup \{k\}$.

By (IIS), $\varphi_i(c)$ is uniquely determined for each $i \notin \uparrow_S (k)$. We obtain that $\varphi(c)$ is uniquely determined from any combination of axioms from the statements 1 and 3.

Regarding statement 2, (NC) and (IIS) implies that $\varphi_i(c) = \varphi_i(c^k)$ for each $i \neq k$; in which case, $\varphi_i(c)$ is uniquely determined. By definition of an allocation method, $\varphi_k(c) = \sum_{i \in N} c_i - \sum_{i \in N} c_i^k = c_k$. We obtain that $\varphi(c)$ is uniquely determined.

This concludes the induction step, and the proof of the theorem. □

	Indep. Irrel. Suppliers (ISS)	Sym. Contrib. (SC)	m-Balanced Contrib. (m-BC)	Null Contrib. (NC)
φ^{S}	+	−	−	+
φ^{DES}	+	+	−	−
$\varphi^{D(m)S}$	+	−	+	−

Figure 2: Overview of proposed allocation methods and their corresponding axioms. (+) denote axioms satisfied by the allocation method considered. Conversely, (-) denotes axioms that are not satisfied by the allocation method.

Remark 1. The allocation problem studied here is mathematically equivalent to the *polluted river problem* of Ni and Wang [37], where agents along river segments (modeled as a directed tree) share the costs of cleaning each segment to meet quality standards. The *Downstream Equal Sharing* and *Standalone* methods were originally proposed by Ni and Wang [37], while the *Downstream Metric Sharing* is based on the *Weighted Upstream Sharing* rule of Li et al. [39] and the broader approach of Gomez et al. [40]. Theorem 1 can be viewed as an extension of the axiomatic results proposed in Lardon and Lowing [41]. Therefore, our work adapts established theoretical results to a supply chain context.

Remark 2. Li et al. [39] provide an axiomatic characterization of Downstream Metric Sharing (referred to as Weighted Upstream Sharing in their framework) that does not rely on a parameterized axiom, unlike our approach. Doing so, their characterization endogenously determines the metric, whereas ours does not. We nevertheless retain the m-Balanced Contribution axiom in order to obtain three directly comparable characterizations. Although the use of a parameterized axiom may render the characterization less compelling from an axiomatic perspective, it facilitates a cleaner comparison across the three sharing rules.

4 Application

This section aims to demonstrate the applicability of allocation method theory and provide insights into their outcomes. To do so, we apply the defined allocation methods to dummy average supply chains reconstructed from Input-Output tables and competitiveness statistics.[4]

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[4] The associated Python code for this application is available as supplementary material.

4.1 Methods and data

4.1.1 Average supply chain structures and emission levels

First, in the absence of readily available empirical corporate data, we build on previous work to reconstruct industry and country specific plausible supply chain structures. Structural Path Analysis (SPA) is a decomposition technique that unfolds the Leontief inverse matrix into a Taylor series expansion, effectively unraveling the aggregate linkages of an input-output system into discrete, hierarchical production chains. This approach allows for the identification of specific high-impact subprocesses within a supply chain tree, but identifies an infinite number of paths and upstream impacts [42]. We refine the SPA method to generate finite upstream industrial supply chains that distribute the root firm's consumption-based impact among its suppliers, ensuring a coverage threshold of at least 95% of the total impact.

In practice, Environmentally Extended Input-Output tables are represented as a set of matrices and vectors. In this study, we leverage three of these elements : the direct requirement matrix A, and the matrix of direct impact F, and the consumption-based impact accounts vector D^{cba}. Let $R-I$ be the set of region-industry pairs. A, the direct requirement matrix, is defined as a $|R-I| \times |R-I|$ matrix of the $a_{i,j}$ where, for all i, j in $R-I$, $a_{i,j}$ denotes the monetary input from sector i required to produce one monetary unit worth of output by sector j. S, the direct impact matrix, is defined as a $|R-I| \times |R-I|$ diagonal matrix of the $s_{i,i}$ where, for all i in $R-I$, $s_{i,i}$ denotes the direct GHG emissions observed per monetary unit worth of output by sector i. M is a $|R-I|$ vector which stores the consumption-based impacts intensities for each region-industry pair, i.e. the total direct and upstream supply chain impacts per unit of final demand for the considered industry in the considered region.

For each region-industry pair, we build an average supply chain by following a iterative procedure inspired by SPA, summarized in Figure 3. Let i_0 be our initial region-industry pair, for which we assume a final demand of 1 monetary unit. i_0's direct emissions are s_{i_0,i_0} and total consumption impact m_{i_0}. Leveraging the direct requirement matrix A, we identify the set of all region-industry pairs the production of i_0 depends on, i.e. all j in $R-I$ for which $a_{i_0,j}$ is non null. Their direct emissions for one unit of monetary output of i_0 will be their direct emissions per monetary unit of output $s_{j,j}$, multiplied by $a_{i_0,j}$, the monetary flow between i_0 and j. Similarly, their direct and indirect contribution to the consumption impact of one monetary unit of our initial region-industry pair is m_j multiplied by $a_{i_0,j}$, the monetary flow between i_0 and j. We order J_1 by decreasing total consumption-based impacts, and add nodes to the tree until the direct and upstream contributions of the included nodes cover 95% of i_0's total consumption impact m_{i_0}. We then iterate by adding upstream nodes to the node with the largest consumption-based impact until reaching a 95% coverage of its direct and indirect contribution to the consumption impact of one monetary unit of our root node.

The iterative process terminates as soon as the sum of direct emissions of nodes added to the tree surpasses 95% of the initial node consumption based impact, ensuring a faithful yet compact representation of direct and upstream emissions of our root node. In order to keep our trees a reasonable size, we do not add upstream nodes when the indirect contribution to the consumption impact of one monetary unit of our initial region-industry pair is less than 1% of total upstream impacts. We nevertheless allocate the relative upstream emissions to the node so as not to cutoff emissions and ensure our final tree effectively covers 95% of the initial nodes direct and indirect emissions.

This process yields a tree structure of region-industry nodes, which we map to the firm level by assuming each node is represented by a single independent company. This is necessary as our theoretical model precludes the circularity that would arise if a single firm appeared more than once or if two firms purchased from the same supplier. [5]

We apply this supply chain reconstruction process on EXIOBASE version 3.9.5 a global, detailed Multi-Regional Environmentally Extended Input-Output Table database ([43, 44]), and consider data from 2019. Input-Output tables manipulations are performed through Pymrio [45].

4.1.2 Exogenous weighting metrics mapping

We pair these reconstructed supply chain trees with micro-level country and industry specific exogenous metrics from the CompNet database, which contains European statistics for various metrics pertaining to corporate finance, labor, and productivity, among others [46]. Among the available CompNet datasets, we consider data relative to the year 2019, the latest 10th vintage release, the ”20e” sample, which includes only firms with 20 or more employees for improved cross-country comparability, and the weighted dataset which corrects for any sampling bias in the underlying raw data using industry representative weightings.

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[5] Note that in the resulting tree, emission levels are normalized by the total demand of the root region-industry pair, hence these values must be scaled by an example root firm's revenue to derive plausible absolute emission estimates. In the following, we consider only relative results so we ignore this consideration.

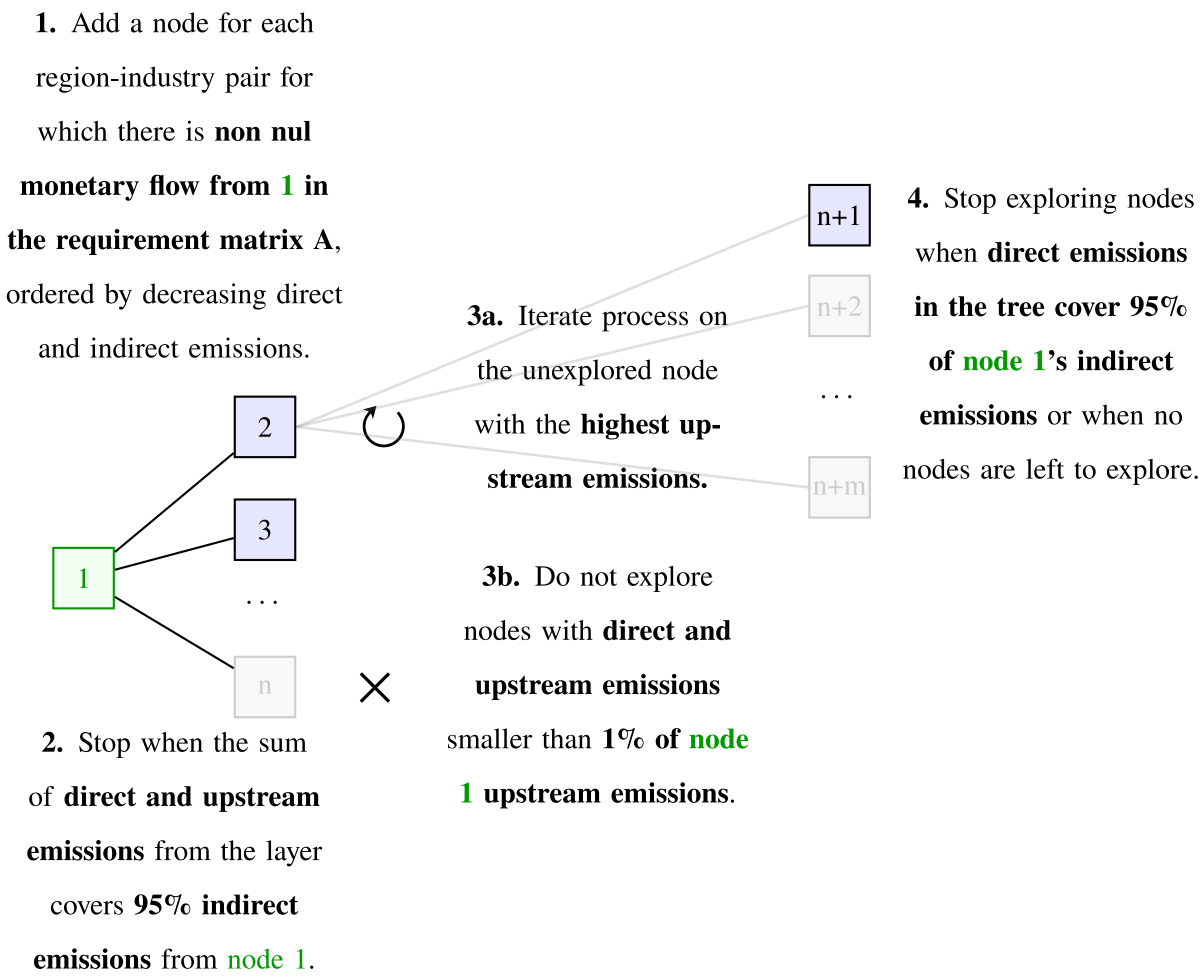

Figure 3: Visual representation of the supply chain construction process from an Input-Output table. For the sake of clarity, only two node layers are represented, but supply chain tree can have more depth, as shown in section 4.2.

Given the existing allocation principles and the available data in the CompNet database [47], we consider several exogenous metrics to illustrate the outcomes of the Downstream Metric Sharing method: direct emissions intensity to operationalize the green incentive approach; historical emissions (estimated as the product of average firm age, direct emissions intensity, and average operating revenue) for the responsibility approach; the reciprocal of average firm profit margin for the economic contribution approach; and the reciprocal of employee count for the social contribution approach [29].[6]

We match each node with average values of each exogenous variables on a country and NACE

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[6] Note that, in line with previously discussed literature ([48, 23]) we do not consider legacy (e.g. grandfathering) as a ”fair” allocation approach here, and other metrics could be considered.

division basis, with the following exceptions. First, when one Exiobase industry maps to multiple NACE divisions (see the official mapping from [43]), we use the average metric across those divisions. Second, when the considered country is not covered by the CompNet dataset, we take as default value the average across all available countries for the considered industry. Third, data availability varies across NACE divisions, and in particular, CompNet only covers secondary and tertiary activities. In the absence of satisfactory default values, we ignore firms in NACE divisions with missing metrics when allocating emissions, effectively treating them as standalone entities responsible only for their direct emissions, while our allocation methods are applied to the remaining tree structure.

4.2 Results

In the following section, we first present example allocation results for a specific industry-country pair, followed by a general outlook on the resulting global burden sharing if all French companies were to follow our collaborative allocation methods.

4.2.1 Selected example

We choose to present the results of our application process for the Exiobase industry ”Processing of meat cattle” (which corresponds to NACE division 10 ”Manufacture of food products”) in France. We argue this example showcases the complexity of supply chain construction and emissions allocation while keeping a reasonable size which facilitates result interpretation.

Figures 4 presents the reconstructed supply chain tree for the industry. [7] In the depicted value chain, the majority of emissions occur upstream in tiers one supplier of the cattle farming industry. The most prominent supplier of the supply chain generates roughly 80% of total consumption based impacts, while other suppliers (including tiers 2 crop suppliers (NACE division 01), fuel suppliers (NACE division 19), wholesale suppliers (NACE division 46), and tiers 1 waste management companies (NACE division 38)) generate at most a few percents of total emissions.

Figure 5 showcases the results of applying previously introduced allocation methods to this example reconstructed supply chain. A few observations can be drawn from this set of graphs. First, regardless of the allocation method applied, the root node's abatement responsibility increases. This directly results from our downstream emissions distribution logic, in which the root node remains responsible

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[7] Figure 12 available in appendix displays the complete set of nodes generated by our supply chain-building procedure. Given the large number of nodes included, the following discussion focuses on the nodes representing more than 1% of total tree emissions in the following paragraph, as depicted in Figure 4.

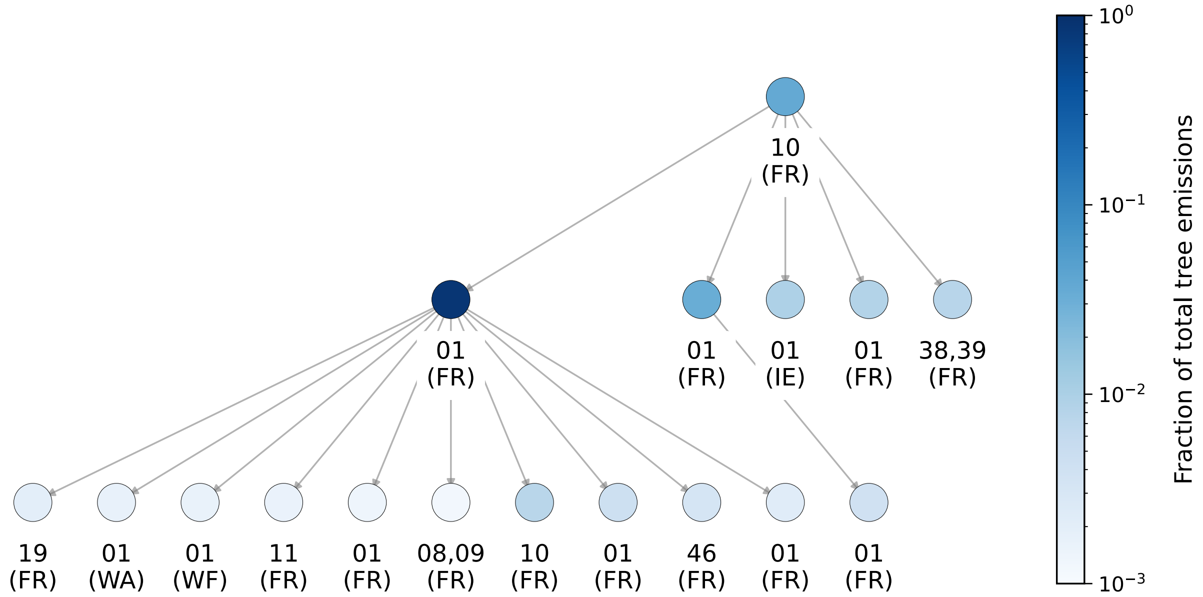
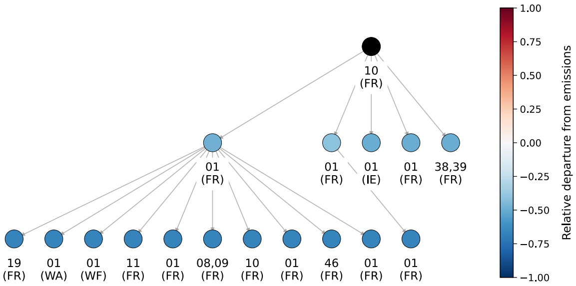


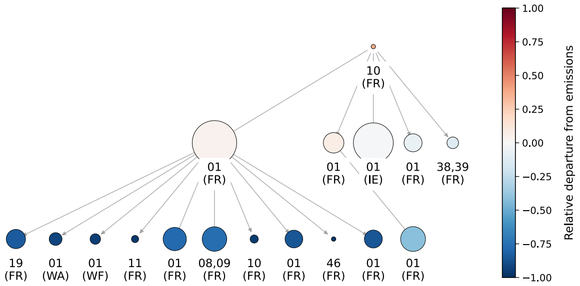
Figure 4: Standalone emissions allocation results for the Processing meat cattle industry in France. Only nodes representing more than 1% of the total upstream footprint are represented.

for abating at least its direct emissions. Second, switching from Standalone to Downstream Equal Sharing or Downstream Metric Sharing allocation methods pushes the responsibility of upstream emissions towards the lower nodes. Using the Downstream equal sharing method, the pass-down is directly proportional to supply chain tiers. Conversely, when using the Downstream metric sharing method, the intensity of this reallocation depends on the chosen allocation metric and its repartition among supply chain members. For instance, the French cattle farming industry has much higher direct emissions intensity than their upstream and downstream counterparts. In Figure 5b, 01FR nodes thus keep the responsibility for a large fraction of their direct emissions, and are allocated a large fraction of their upstream suppliers emissions, to the point where their abatement responsibility increases slightly compared to a standalone setting. On the contrary, the French meat processing industry presents lower profit margins than their suppliers, which moderate their emissions abatement responsibility allocation when using Downstream profit margin sharing. Despite these differences, the order of magnitude of emissions allocated to nodes typically remains constant and remains representative of the contribution of each node to the total consumption footprint of the root industry.

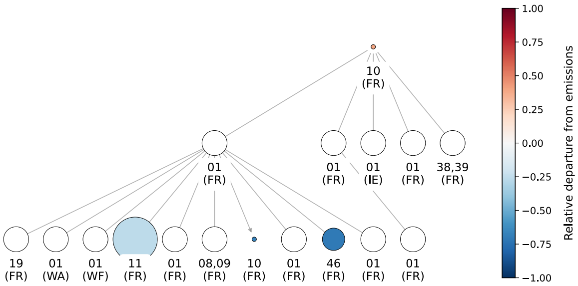
All and all, the choice of allocation methods can thus significantly affect the burden sharing distribution for a given value chain, but keeps in consideration the supply chain structure and distribution of direct emissions. As such, their application can result in a range of outcomes depending on the root firm considered.



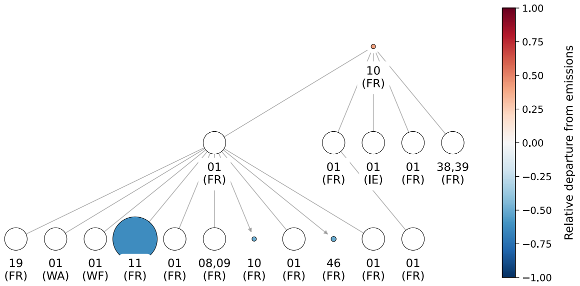
(a) Relative departure from Standalone allocation when applying Downstream Equal Sharing.



(b) Relative departure from Standalone allocation when applying Downstream direct emissions intensity Sharing. Node sizes are proportional to direct emissions intensities.

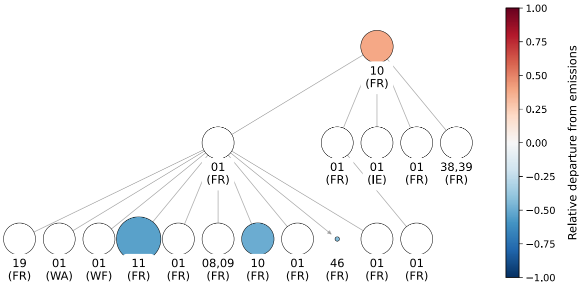


(c) Relative departure from Standalone allocation when applying Downstream historical emissions Sharing. Node sizes are proportional to direct historical emissions.



(d) Relative departure from Standalone allocation when applying Downstream profit margin Sharing. Node sizes are proportional to profit margins.

Figure 5: Emission allocations results for the reconstructed supply chain of the Exiobase industry ”Processing of meat cattle” in France using Downstream Equal Sharing and Downstream Metric Sharing with a range exogenous metrics operationalizing various equity principles. Node labels indicate industries using rev2 NACE divisions ([49]) and countries as described by the ISO 3166 international standard [50]. Black nodes indicate firms for which the emissions abatement responsibility more than doubled. White nodes present missing data and are ignored by the allocation method.



(e) Allocation of emissions using Downstream Metric number of employee Sharing. Node sizes are proportional to number of employees.

Figure 5: Emission allocations results for the reconstructed supply chain of the Exiobase industry ”Processing of meat cattle” in France using Downstream Equal Sharing and Downstream Metric Sharing with a range exogenous metrics operationalizing various equity principles (continued).

4.2.2 Generalization across industries in France

To discuss allocation results beyond firm-level variability, this paragraph illustrates the global burden-sharing distribution that would result from the comprehensive implementation of these collaborative practices by all firms operating in France. To estimate this distribution, we reconstitute supply chains for all Exiobase industries in France following the process described in paragraph 4.1.1, scale them by multiplying emission metrics in each tree by the root node’s 2019 global final demand (leveraging the total demand matrix Y from Exiobase), and finally sum the allocations for a given region-industry pair across supply chains. Note that in line with the data availability issues discussed in section 4.1.2, we prune the trees from region-industry pairs for which exogenous allocation metrics are not available, and allocate them the totality of their direct emissions. We first present the consumption footprint of French production in the absence of distributive efforts (as would result from the Standalone allocation method), and then present how each allocation method departs from this initial footprint.

Figure 6 presents repartition of the consumption footprint of France across regions and industries. As expected, upstream impacts are not distributed uniformly across industries and regions. In particular, foreign upstream emissions are negligible for industries with comparatively low direct emissions intensities, such as service and associative industries (NACE divisions 58-94), and health and education (85-86). Further, while their emissions are globally relevant, our decomposition estimates emissions of foreign local primary industries such as extractive activities (07-09), waste disposal (38-39), and water treatment and distribution (36-37), are negligible. That is because they lie too far upstream in the supply chain to be considered by our simplified tree building algorithm, which does not explore nodes representing less 1% of total root node upstream emissions. Their emissions are nevertheless considered in our allocation procedure, as they are integrated to the emissions of the downstream sectors they contribute to fueling. Beyond these industries, emissions clusters appear in the agriculture (01), manufacturing (19-26, and 28-33) and wholesale sectors (49-56) in countries such as China (CN), Belgium (BE), Germany (DE), Spain (ES), Great Britain (GB), Indonesia (IN), Italy (IT), the Netherlands (NL), Poland (PL), the United States (US), and the rest of the world regions (WA (Rest of the world Asia and Pacific), WE (Rest of the World Europe), WF (Rest of the World Africa), WL (Rest of the World America) and WM (Rest of the World Middle East)). Nevertheless, the majority of emissions linked to French consumption occur on the French territory, as demonstrated by the prevalence of emissions on the line corresponding to domestic impacts (note that the scale of the heatmap is logarithmic).

Figure 7 depicts the relative change in allocation for each region-industry pair if all French firms would apply Downstream Equal Sharing instead of a standalone logic. Conformably to what was expected, emissions abatement responsibilities in all foreign countries and industries involved in the French consumption drop from 25 to 75%, depending on the region and industry considered. For instance, the electricity production and distribution and waste and water management (35-38) and industries located in Indonesia display higher reduction in abatement responsibility on average. One exception to the general reduction are health, art and social services in Rest of the World regions which get allocated higher emissions abatement responsibilities due to high indirect emissions and an end-of-pipe position. Conversely, with some exceptions, all French industries are responsible for an increased share of emissions, with relative growth being the most important in low-direct emissions customer facing industries such as services (58-75) and textile and food product manufacturing (10-15). Note that while some French industries benefit from the application of this alternative allocation method, they benefit relatively less than foreign competition due to their more direct links with final demand industries.

Figures 8, 9, 10 and 11 display the relative change in allocation for each region-industry pair if all French firms would follow a Downstream Metric Sharing allocation system with direct emissions intensities, historical emissions, profit margin and number of employee as exogenous metrics instead of a standalone allocation method. Throughout all equity metrics, the downstream distribution logic dominates and upstream foreign suppliers and domestic upstream suppliers are generally alleviated of emissions, which are allocated to French industries. One exception is the downstream profit margin allocation, which results in a range of foreign industries bearing a higher emissions abatement responsibility than their standalone share. We attribute this to the existence of low-direct emissions, high-profit, high-indirect emissions industries, such as printing and editing (18, 58, 59).

While the downstream logic dominates, the magnitude and distribution of removed responsibility nevertheless depends on the chosen proportionality metric. For instance, considering profit margins strongly accentuates the downstream logic, particularly in primary and secondary sectors, as financial benefits appear concentrated within customer facing industries, whereas considering emissions intensity as the proportionality metric almost nullifies benefits for foreign actor in primary and secondary sectors, while further reducing emissions abatement responsibilities for low-emissions services and support industries. Similarly, services activities bear a significantly reduced burden when considering historical emissions, while their responsibility is kept close to standalone when considering number of employee as proportional metric.

Choosing an exogenous metric symmetrically affects domestic allocation : the lower the allocations upstream, the higher the raise in domestic allocations. However, this combines with industry specific changes detailed above : for instance, the responsibility for abating emissions of service industries using downstream emissions intensity sharing is reduced compared to downstream equal sharing.

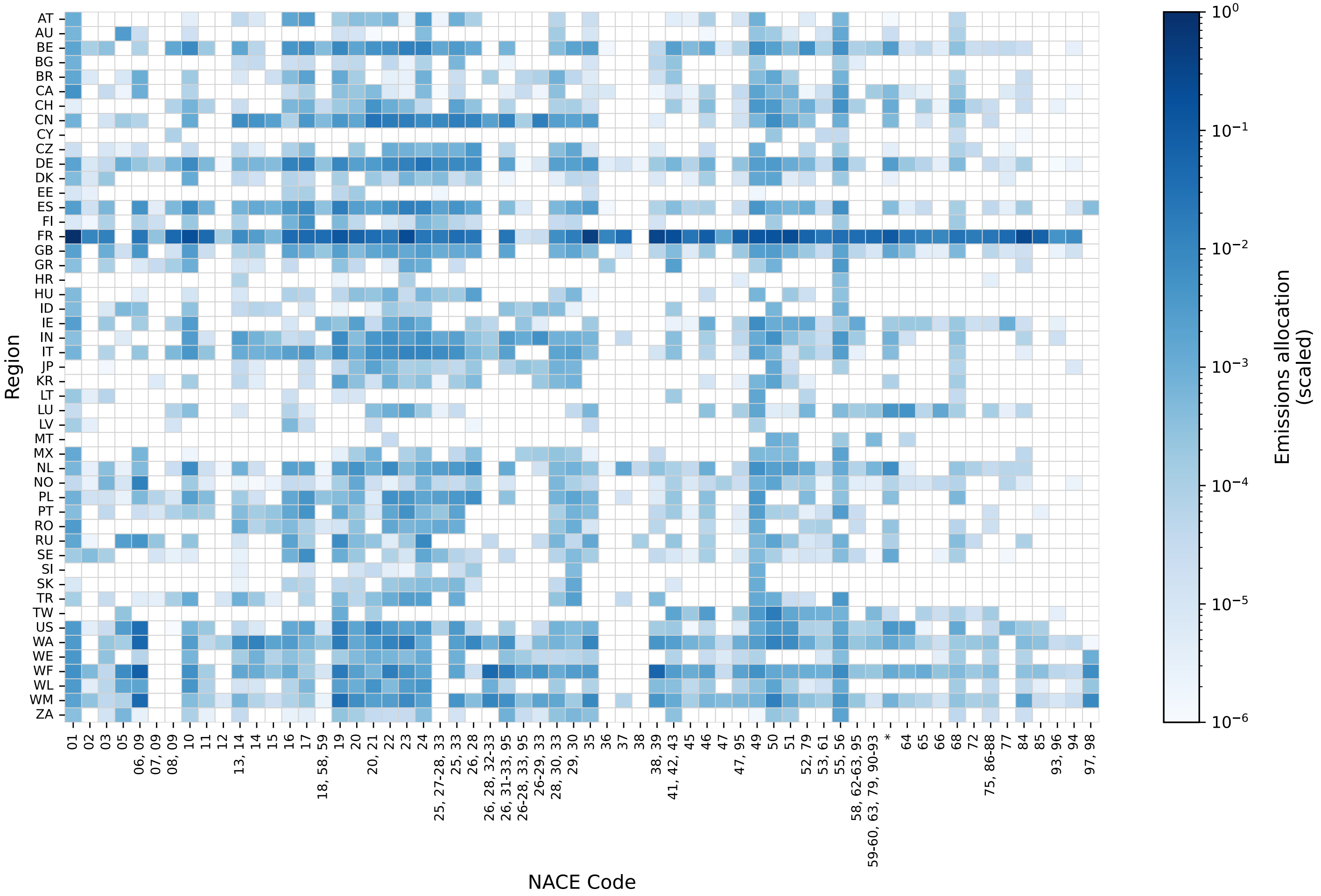


Figure 6: Heatmap of the distribution of France's consumption footprint across global regions and industries. Regions can be identified through their ISO 3166 code [50], and industries through their NACE rev2. level 2 code [49]. * denotes an aggregated cluster of NACE codes 63-64, 69-71, 73-74, 77-78, 80-82 and 85, for which the label was removed to minimize visual clutter. Emissions are scaled from 0 to 1, and for visualization purposes, only relative impacts greater than 10^{-6} are shown.

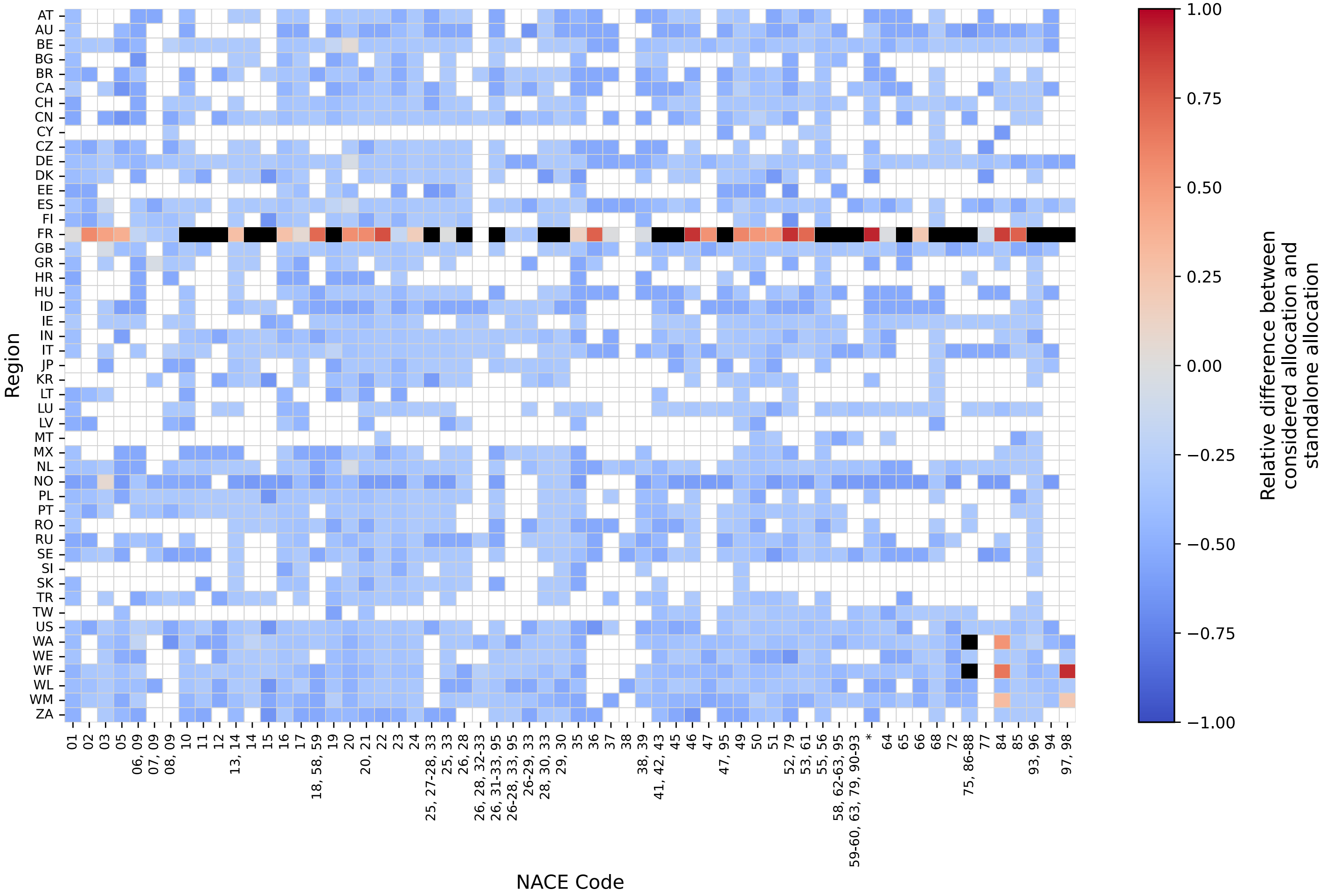


Figure 7: Relative change in allocation of emissions when switching from the standalone to the Downstream Equal Sharing allocation method for each region-industry pair. Regions can be identified through their ISO 3166 code [50], and industries through their NACE rev2. level 2 code [49]. Black entries identify region-industry pairs where emissions allocation more than doubled following the change in allocation metrics. * denotes an aggregated cluster of NACE codes 63-64, 69-71, 73-74, 77-78, 80-82 and 85, for which the label was removed to minimize visual clutter.

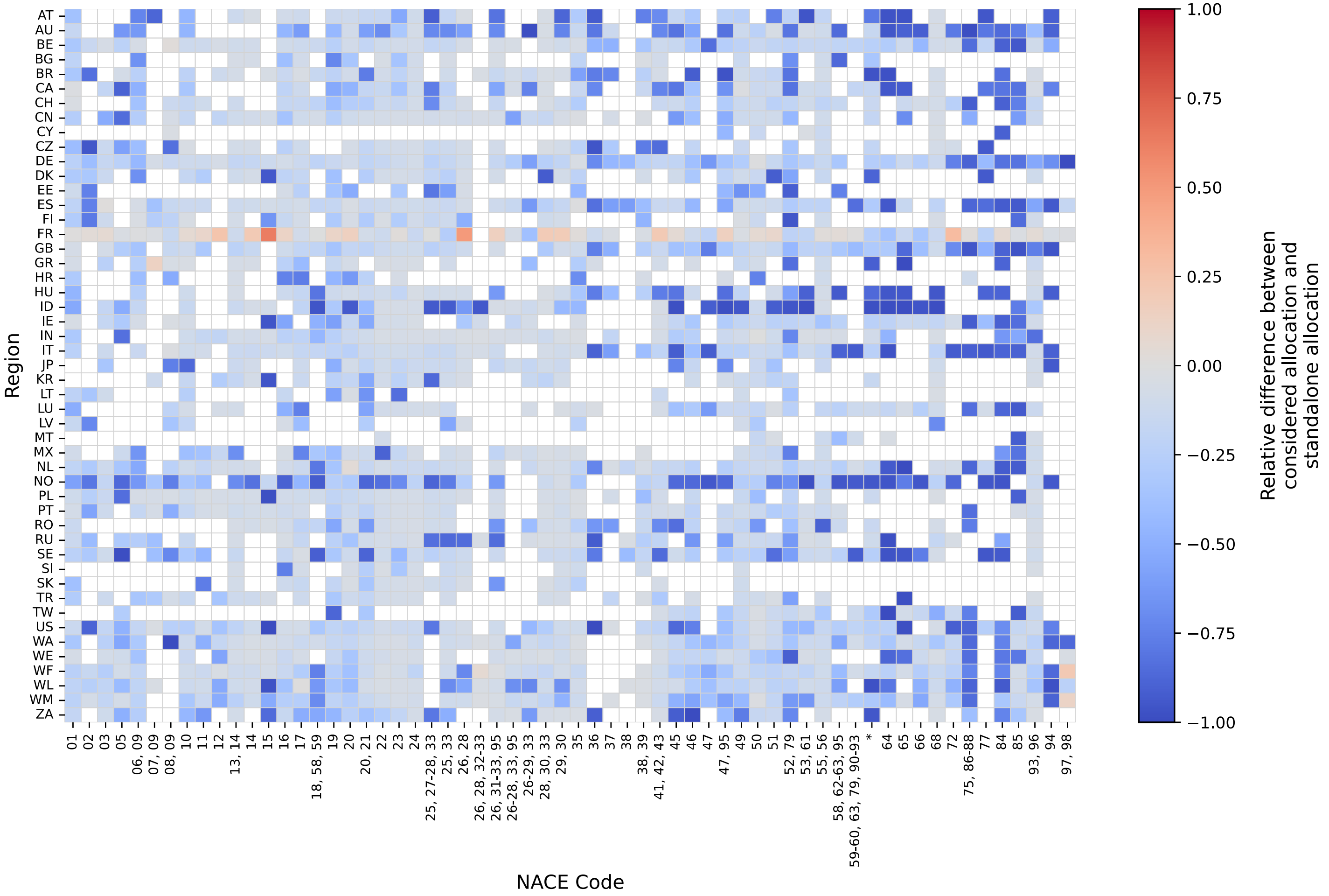


Figure 8: Relative change in allocation of emissions when switching from the standalone to the Downstream Metric Sharing allocation method with emissions intensity as an exogenous metric. Regions can be identified through their ISO 3166 code [50], and industries through their NACE rev2. level 2 code [49]. Black entries identify region-industry pairs where emissions allocation more than doubled following the change in allocation metrics. * denotes an aggregated cluster of NACE codes 63-64, 69-71, 73-74, 77-78, 80-82 and 85, for which the label was removed to minimize visual clutter.

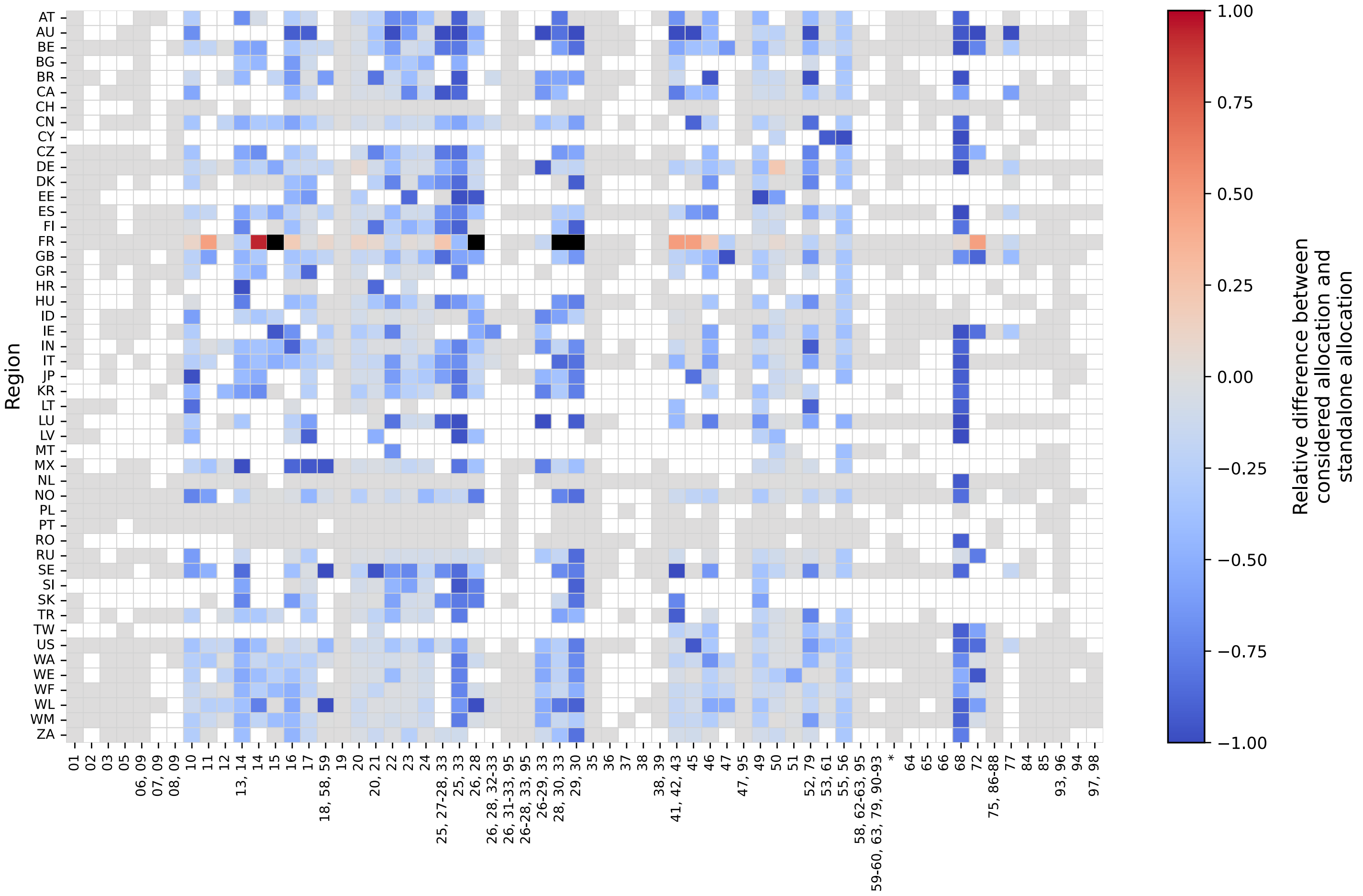


Figure 9: Relative change in allocation of emissions when switching from the standalone to the Downstream Metric Sharing allocation method with historical emissions as an exogenous metric. Regions can be identified through their ISO 3166 code [50], and industries through their NACE rev2. level 2 code [49]. Black entries identify region-industry pairs where emissions allocation more than doubled following the change in allocation metrics. * denotes an aggregated cluster of NACE codes 63-64, 69-71, 73-74, 77-78, 80-82 and 85, for which the label was removed to minimize visual clutter.

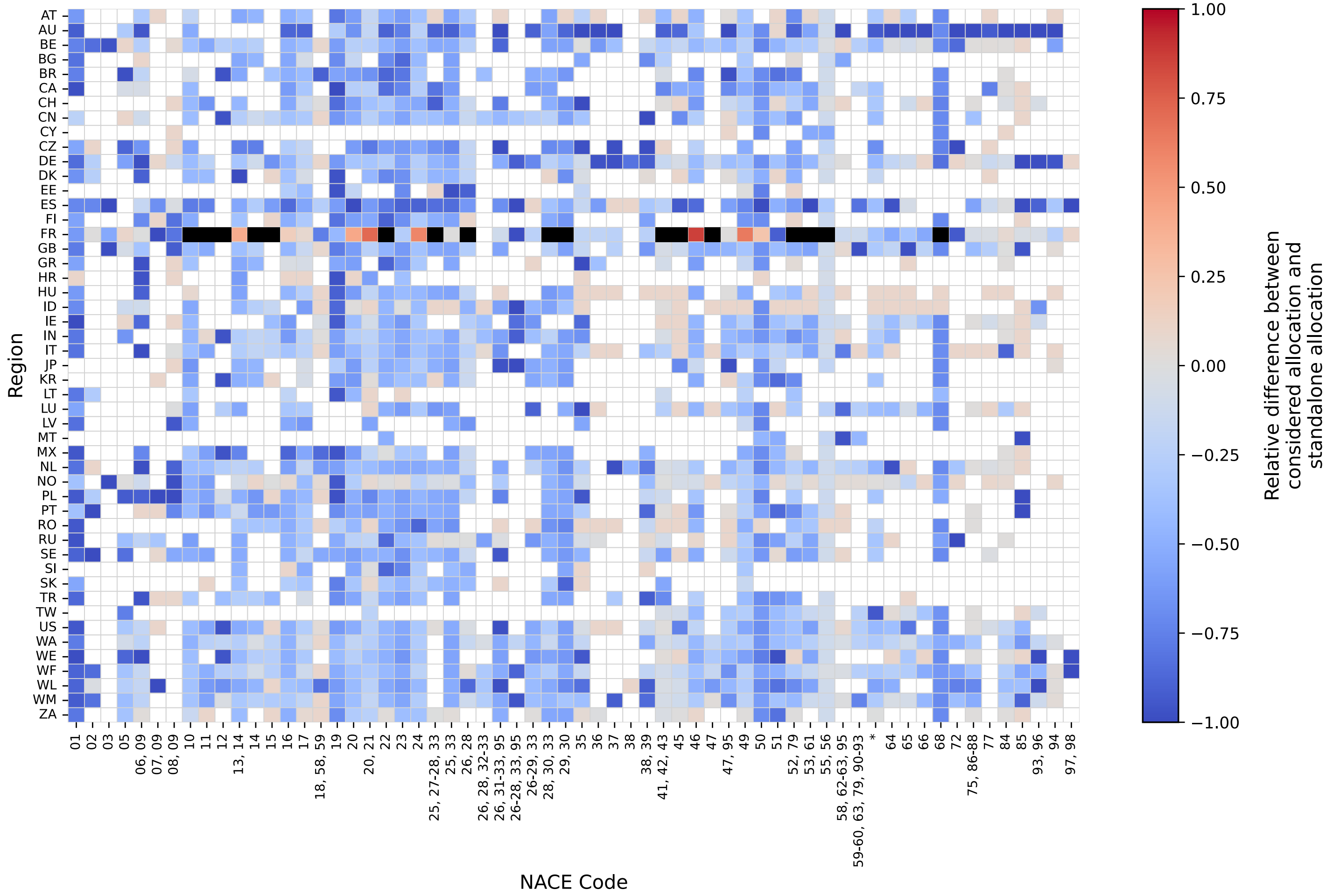


Figure 10: Relative change in allocation of emissions when switching from the standalone to the Downstream Metric Sharing allocation method with firm profit margin as an exogenous metric. Regions can be identified through their ISO 3166 code [50], and industries through their NACE rev2. level 2 code [49]. Black entries identify region-industry pairs where emissions allocation more than doubled following the change in allocation metrics. * denotes an aggregated cluster of NACE codes 63-64, 69-71, 73-74, 77-78, 80-82 and 85, for which the label was removed to minimize visual clutter.

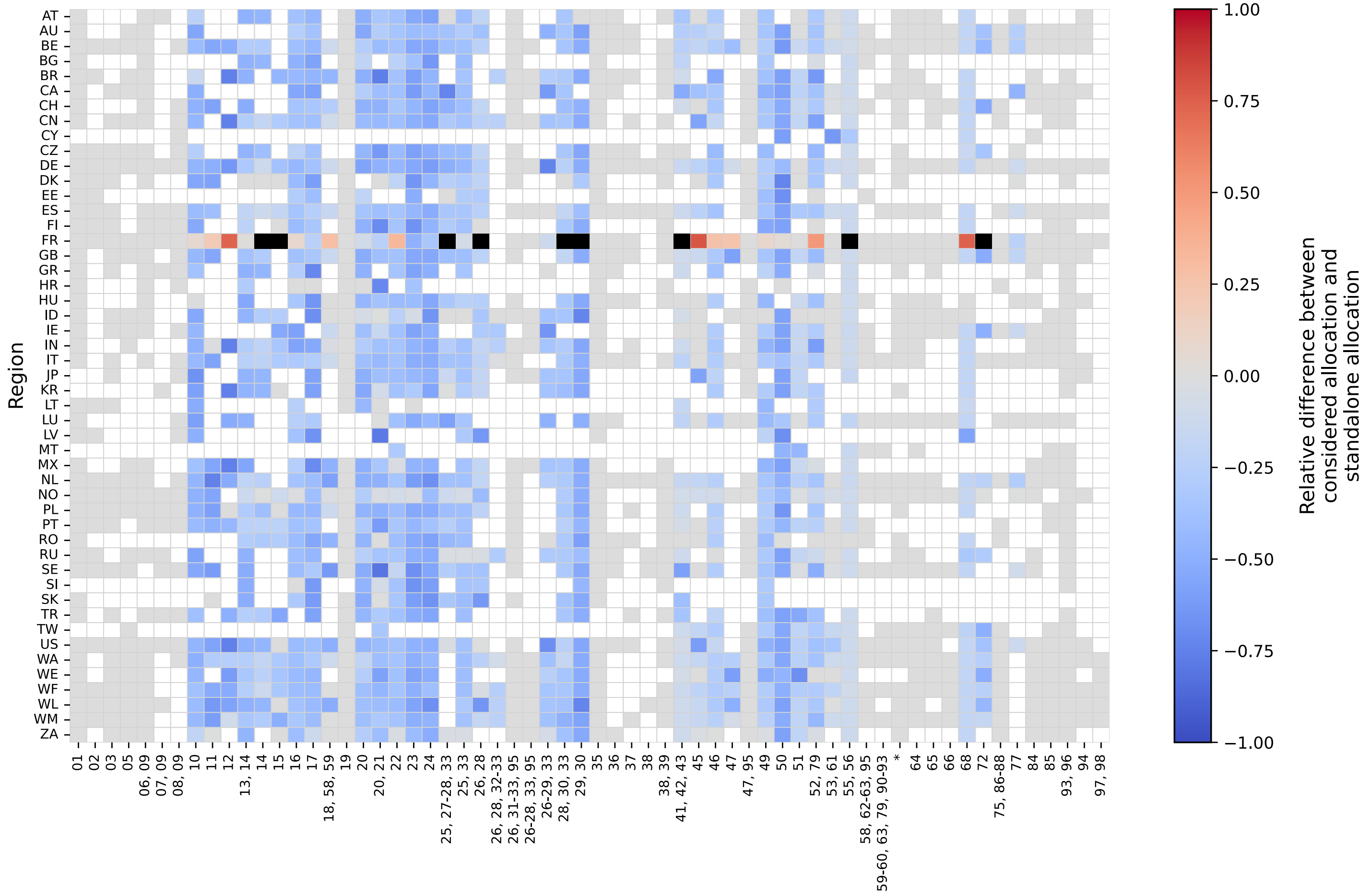


Figure 11: Relative change in allocation of emissions when switching from the standalone to the Downstream Metric Sharing allocation method with number of employees as an exogenous metric. Regions can be identified through their ISO 3166 code [50], and industries through their NACE rev2. level 2 code [49]. Black entries identify region-industry pairs where emissions allocation more than doubled following the change in allocation metrics. * denotes an aggregated cluster of NACE codes 63-64, 69-71, 73-74, 77-78, 80-82 and 85, for which the label was removed to minimize visual clutter.

5 Concluding remarks

Despite the urgency of addressing climate change and the diversity of academic work outlining fairer allocation practices, corporate supply chain emissions management can be coercive. This work proposes novel, theory-based methods for allocating upstream emission responsibility among interdependent firms in an effort to replace these coercive practices and obtain fairer outcomes.

The core contributions of this study are threefold. First, we applied allocation methods from the polluted river literature to our framework. We then provided axiomatic characterizations of these rules, enabling a clear and systematic comparison among them. Second, in the absence of readily available supply chain data, we extend the previously established Structural Path Decomposition technique to empirically reconstruct multi-tier supply chains from input-output databases, and complement them with firm-level exogenous metrics from the CompNet database. Third, we apply the considered allocations methods to a range of industries, and show that all downstream allocation methods shifts emissions abatement responsibility from upstream foreign suppliers towards the downstream domestic suppliers, with varying intensities and industry-specific variations depending on allocation principle choices.

These novel allocation methods could integrated into voluntary corporate carbon standards such as *SBTi* to avoid the potentially unfair outcomes of current supplier management practices. First, target setting standards could recommend companies implement financial support transfers to their upstream suppliers to mimic our allocation results. Further, these allocation methods could be articulated with industry specific total emissions abatement targets. We propose a two-step supply-chain wide allocation method : first, the supply chain gets allocated a share of the safe operating space that, confronted with their current total footprint, determine their common abatement objective ; second, actors negotiate and share the abatement responsibility our one of our equity embedded allocation methods. Although this second approach requires revising existing standards, it enables supply chain flexibility in selecting equity principles while maintaining transparent target-setting and preventing global carbon budget overshoots—addressing two persistent issues in the current framework [51, 52]. However, end-of-chain actors might be reluctant to voluntarily adopt these allocation methods, given any downstream sharing method is likely to increase their emissions abatement responsibility. This is an important concern given they represent the majority of companies who have set or have committed to set *SBT* [6]. Similarly, consumers could be wary of the increased threat of cost pass down if consumer-facing companies finance the emissions reduction upstream their supply chains.

Despite these contributions, this study presents limitations that warrant further research. First, this study suffers various data-availability limitations. A central issue is the representativeness of our input-output table-derived supply chains and average exogenous equity metrics. Our work might thus benefit from further application on empirical industrial supply chains and variability testing. Similarly, we were not able to operationalize and discuss the complete range of fairer allocation principles, nor to explore the full range of possible operationalization metrics across principles. Second, further work could try to adapt our allocation methods to make them applicable to directed graphs, which are likely to offer a more robust representation of complex firm supply chains, and to make them cover final demand emissions, which are left unaddressed by our allocation methods. Finally, this research could be expanded by applying these allocation methods across countries, thereby providing a comprehensive overview of allocation outcomes given current global trade patterns.

Acknowledgments

We thank Dr. Emma Jagu Schippers, Coline Seralta, Erwan Petit de Bantel, and Dr. Benoît Dabouis for the meaningful discussions that contributed to the conceptualization of this work. This work also benefited from insightful comments from Prof. Anders Bjørn, Prof. Philippe Quirion, and Prof. Carolyn Fischer.

Declaration of generative AI

During the preparation of this work the authors used various large language models to assist with writing clarity and code development. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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6 Appendix

Algorithm 1: Downstream Equal Sharing

```
// Initialize all allocations to zero
$\varphi \leftarrow (0, \ldots, 0)$
// Enumerate over all firms
for $j \in N$ do
    // Consider all firms supplied by $j$ and $j$ itself
    for $i \in \uparrow_S (j) \cup \{j\}$ do
        // Assign each of them an equal share of $j$'s direct emission
        $\varphi_i \leftarrow \varphi_i + c_j / |\uparrow_S (j) \cup \{j\}|$
    end
end
Result: $\varphi$
```

Algorithm 2: Downstream Metric Sharing

```
// Initialize all allocations to zero
$\varphi \leftarrow (0, \ldots, 0)$
// Enumerate over all firms
for $j \in N$ do
    // Consider all firms supplied by $j$ and $j$ itself
    for $i \in \uparrow_S (j) \cup \{j\}$ do
        // Assign each of them a proportional share of $j$'s direct emission
        $\varphi_i \leftarrow \varphi_i + c_j \times \frac{m_i}{\sum_{k \in \uparrow_S (j) \cup \{j\}} m_k}$
    end
end
Result: $\varphi$
```

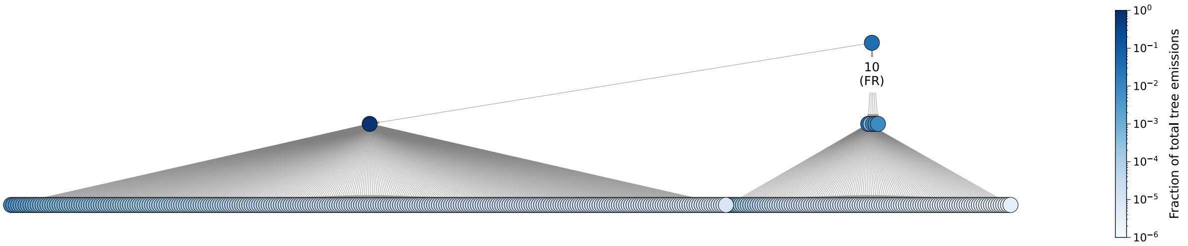

Figure 12: Reconstructed supply chain for a company operating in Exiobase industry Processing of meat cattle in France. Colors denotes the fraction of total emissions the node's direct emissions represent. All nodes have the same size.